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A method for measurement of dynamic compliance of the left ventricle in dogs

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Templeton, Gordon H., Jere H. Mitchell, Roger R. Ecker, and Gunnar Blomqvist. *A method for measurement of dynamic compliance of the left ventricle in dogs.* J. Appl. Physiol. 29(5): 742–745. 1970.—The dynamic compliance of the isovolumic left ventricle in dogs was measured during contraction and relaxation by a new technique. The technique involves the introduction of sinusoidal volume changes into the left ventricle and the measurement of the resulting pressure perturbations. The induced volume changes are of constant displacement and at a frequency from 6 to 12 times the heart rate. Determination of the pressure perturbation magnitudes during contraction was made possible by subtraction of a computer-averaged unperturbed pressure cycle from a comparable perturbed cycle obtained when the volume changes were being induced. The technique was used to investigate the dynamic mechanical properties of the intact left ventricle. The ventricle was found to display greater stiffness during contraction than during relaxation. In addition, a viscous component of cardiac muscle was found to exist both during contraction and relaxation and to have a greater influence during contraction.

ventricular compliance; cardiac muscle; volume stiffness; distensibility; muscle viscosity

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A technique has been developed for measuring the dynamic compliance of the intact left ventricle in dogs during both contraction and relaxation. This technique is an extension of that conceived by Buchthal et al. (2, 3) for skeletal muscle and utilized by Lundin (9) for frog cardiac muscle. These investigators subjected strips of muscle to sinusoidal stretches and measured the resulting changes in tension. Extended to the intact heart, the modified technique induces sinusoidal volume changes of constant displacement (1 ml) into an isovolumically contracting left ventricle at a frequency several times greater than the heart rate. The measurement of the peak-to-peak variations of the pressure perturbations resulting from the induced volume changes provides a means for determining volume stiffness. This term is defined as the ratio of the peak-to-peak pressure change to the induced volume change.

Volume stiffness can be used to characterize the intact ventricle in terms of its dynamic compliance and viscosity. Dynamic compliance, as defined by Remington (12), is a time-dependent quantity and is a ratio of a change in dimension to a change in stress. Dynamic compliance is proportional to the reciprocal of volume stiffness as measured in the present investigation in an isovolumic preparation and characterizes the viscoelastic property of cardiac muscle. In addition to dynamic compliance, the time-dependent viscous component of cardiac muscle was investigated separately from the time-independent quantity, elasticity, by measuring the change in volume stiffness which occurred after a change in the rate at which the volume changes of the flow-pulse generator were induced.

METHODS

Surgical procedures. Mongrel dogs, 15–22 kg, are anesthetized with intravenous sodium pentobarbital, 30 mg/kg. The chest is opened by a sternal-splitting incision, and the rib cage is retracted laterally. The superior and inferior venae cavae are cannulated in order to collect the venous return which is diverted to an extracorporeal circuitry consisting of an oxygenator, heat exchanger, and roller pump. The left carotid artery is cannulated and oxygenated blood is returned to the animal to perfuse the systemic circulation. The right carotid artery is cannulated for measurement of mean aortic pressure. Both vagus nerves and carotid sinus nerves are sectioned in the neck, and complete heart block is produced.

With the heart and lungs isolated from the circulation, the cannula of the flow-pulse generator is prepared for insertion into the ventricular cavity. As shown on the right of Fig. 1, a distensible balloon is slipped over the Teflon button, attached to the metal cannula, and filled with fluid. The balloon is inserted into the left ventricular cavity through an incision made in the apical dimple. The Teflon button within the balloon is positioned to occlude the aortic valve by a modified method of Reis et al. (11), as also shown in Fig. 1. To complete the isovolumic preparation, a perforated Teflon button is sutured in position to occlude the mitral valve. The purpose of the buttons is to retain the balloon within the ventricular cavity.

Flow-pulse generator. A flow-pulse generator was designed to produce known sinusoidal volume changes in a fluid-filled system. The generator consists of an electric motor, a variable-speed transmission, a scotch-yoke, and a piston enclosed in a watertight housing. These components are included in a schematic diagram of the experimental preparation shown in Fig. 2. The input shaft of the transmission is belt driven by the motor (General Electric Motor Division, Fort Wayne, Ind.), which is rated at 0.25 horsepower, 1,725 rpm for 125 v, and 5.2 amps. The output shaft of the ball/disc variable-speed transmission (model Bd4, Graham Transmission, Inc., Menomonee Falls, Wis.), which is rated at an input maximum of 1,750 rpm and an output of 2,600/0 rpm with a maximum torque of 3, is mechanically linked to the scotch-yoke. This device translates the rotary motion of the transmission shaft to translational motion of the piston. With these components, the flow-pulse generator is capable of generating a variable volume displacement between 0 and 5 cm^3 at a frequency from 0 to 30 Hz.

The flow-pulse generator is connected to the canine left ventricle through a fluid-filled system consisting of a low-compliance, thick-walled Lucite tube and a thin-walled, stainless steel cannula shown in Fig. 1. The steel cannula has a side arm through which a pressure transducer (model SF-1, Statham Laboratories, Inc., Hato Rey, Puerto Rico) may be inserted and positioned inside the left ventricular cavity. Through a second sidearm of the cannula, a piece of stiff wire is inserted through a watertight fitting and extended beyond the end of the cannula into the left ventricular cavity. A Teflon button attached to the end of the wire may be twisted, extended, or withdrawn with respect to the end of the can-

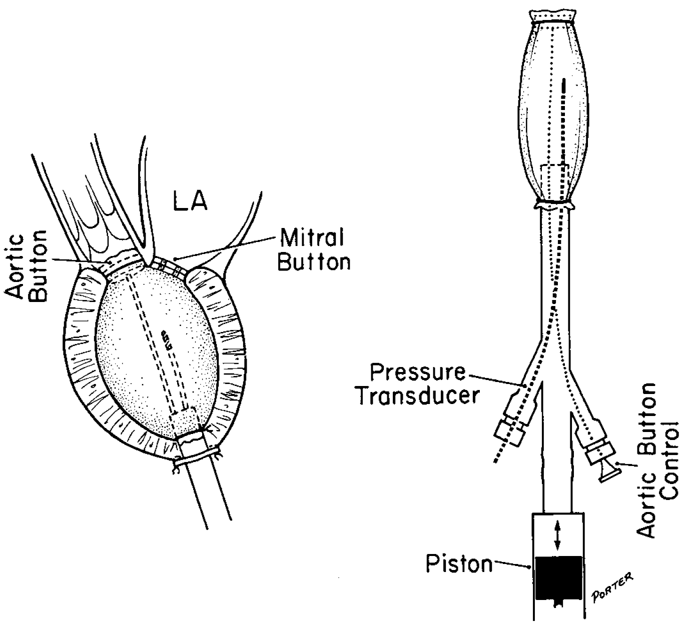

FIG. 1. Preparation of isovolumic ventricle. Saline-filled portion of flow-pulse generator, shown at the right, consists of piston enclosure, Lucite tube, stainless steel cannula with two sidearms, a distensible balloon, and an aortic button. On left is shown isovolumic preparation after inflation of balloon with saline.

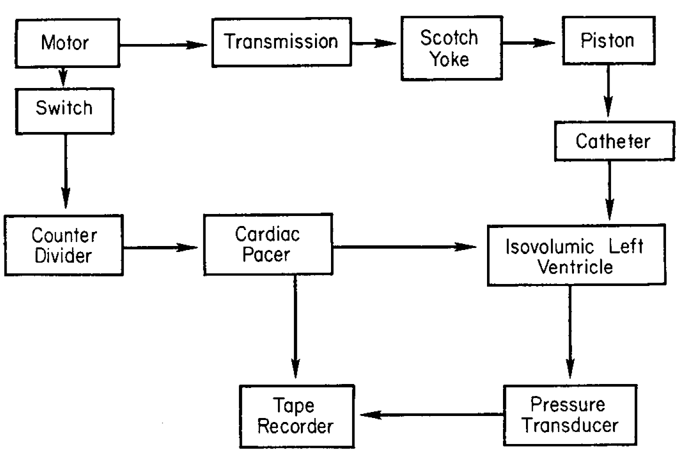

FIG. 2. Schematic of experimental preparation. Flow-pulse generator consists of motor, switch, transmission, scotch yoke, piston, and catheter. Electrical circuitry responsible for pacing heart includes switch, counter divider, and cardiac pacer.

nula by maneuvering the opposite end of the wire for the purpose of occluding the aortic valve.

The heart is paced during the experiment to provide synchrony between the pump frequency and the heart rate. This pacing procedure allows the data to be averaged later on a computer since the resulting pressure perturbations appear at the same points in each ventricular pressure cycle. The pacing circuitry consists of an electrical switch (Kalper switch, MicroSwitch Corp., Freeport, Ill.), a counter (composed of components acquired from Digital Equipment Corp., 3417 Milam St., Houston, Texas 77002), and a stimulator. The switch contacts close with each revolution of the transmission's output shaft. When a preset number of contact closures is reached, an output pulse from the counter triggers the stimulator which, in turn, paces the heart.

Data collection, reduction, and analysis. Experimental data are recorded simultaneously on an oscillograph (Electronics for Medicine, Inc., White Plains, N. Y.) and a tape recorder (model 2000, Sanborn Co., Waltham, Mass.). The oscillograph records mean aortic pressure as measured by a pressure transducer (model P23Db, Statham Laboratories), left ventricular pressure as measured by the SF-1 pressure transducer, and the pressure of another transducer (model P23Db, Statham Laboratories) located on the end of the SF-1 catheter. The purpose of the latter transducer is to measure the zero drift of the SF-1 due to temperature change. The tape recorder records the left ventricular pressure as measured by the SF-1 and a train of pulses used as trigger pulses for the averaging computer; the latter is used to average the SF-1 pressure data. The pulses are generated each cardiac cycle at an output terminal of the stimulator coincidentally with the pulses which pace the heart.

The data on the analog tape are reduced using a computer of average transients (series 4000, Technical Measurement Corp., North Haven, Conn.). The function of this computer is to average the ventricular pressure to remove nonperiodic noise. The data averaged by the computer are available in analog or digital form. The analog data are used for preliminary calculations of dynamic compliance to check for irregularities in the data.

Figure 3 shows a ventricular pressure waveform obtained from an isovolumic ventricle in the upper tracing and a comparable waveform showing the perturbations due to the flow-pulse generator in the lower tracing. In Fig. 4, the averaged pressure waveforms comparable to the real-time data are shown. As shown in Fig. 4, the sweep of the computer was adjusted so that two pressure cycles were included in one averaging operation. Each cycle shown in Fig. 4 represents an average of 25 pressure cycles. The two parts of Fig. 4 represent the two types of data obtained for each intervention under investigation. Both types are required in order that the unperturbed data at the top of Fig. 4 can be subtracted from the perturbed pressure data in the center of Fig. 4 to yield solely the pressure perturbations due to the flow-pulse generator. The result of the subtraction of the two types of data is shown at the bottom of Fig. 4.

The digitized pressure data corresponding to that at the bottom of Fig. 4 are analyzed to determine the peak-to-peak magnitudes of the pressure perturbations (in mm Hg). These perturbation

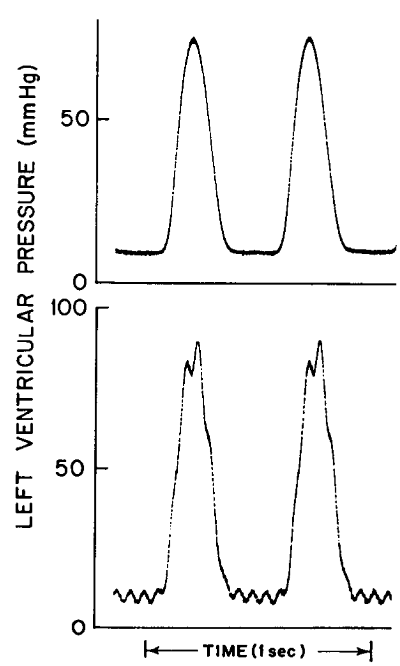

FIG. 3. Ventricular pressures recorded in an isovolumic ventricle before (*top*) and during operation of flow-pulse generator (*bottom*).

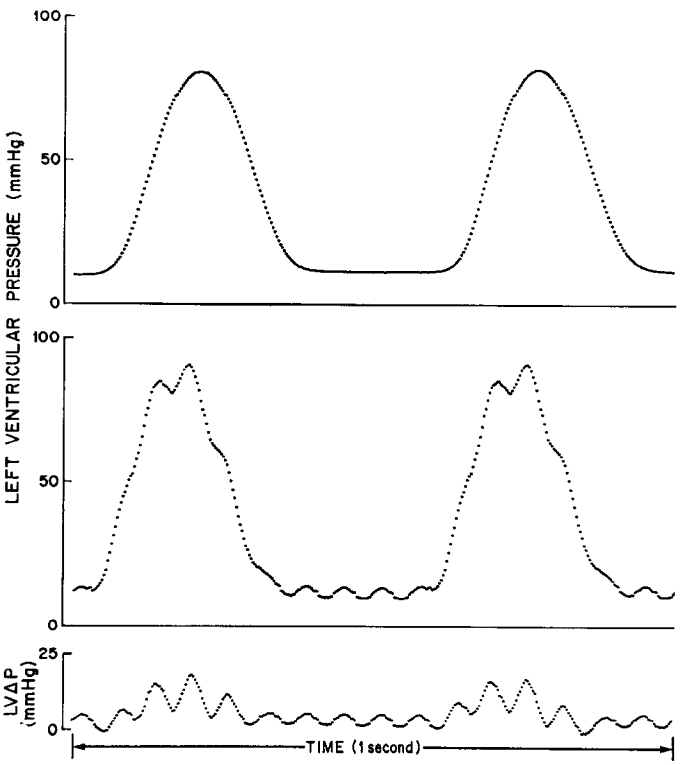

FIG. 4. Averaged ventricular pressure waveforms. Each waveform is an average of 25 pressure cycles and is obtained by computer. Upper and middle waveforms correspond to those of Figure 3, and lower waveform was obtained by subtraction of the upper waveform from middle one.

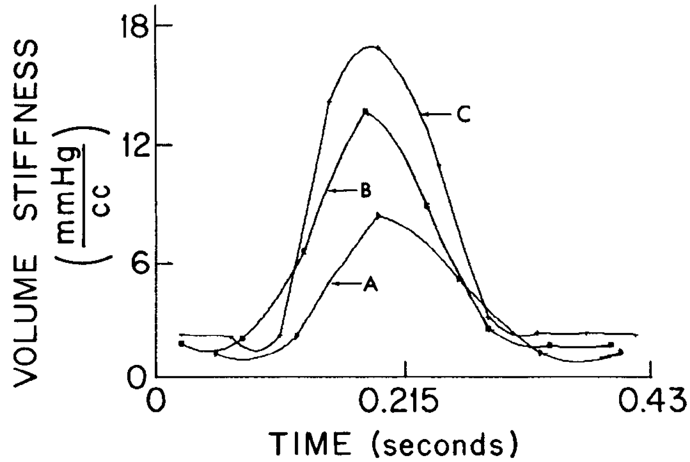

FIG. 5. Temporal variation of volume stiffness obtained for piston frequencies of 14 (curve A), 18.6 (curve B), and 23.3 Hz (curve C).

magnitudes also represent volume stiffness since the peak-to-peak volume change produced by the flow-pulse generator is 1 ml.

Evaluation of method. An isovolumic canine left ventricle preparation is used in conjunction with the flow-pulse generator. This allows measurement of compliance throughout the cardiac cycle. In contrast, the dynamic compliance measured in the nonisovolumic case reflects the dynamic compliance of the left ventricle only during the isovolumic phases of the cardiac cycle. When the aortic valve is open, the dynamic compliance measured would represent a composite of contributions from both the left ventricle and the arterial vascular system. When the mitral valve is open, the dynamic compliance would reflect contributions from the left ventricle, left atrium, and pulmonary vascular system.

The dynamic and static volume stiffness of the flow-pulse generator without the balloon was determined. A glass syringe with the same diameter as the stainless steel cannula was attached to its end. After the cannula and part of the syringe were filled with degassed saline, the fluid used during experiments, a plunger was inserted into the syringe and attached to it with a rubber band. The amplitudes of the plunger's displacement at various piston frequencies were found to be the same, and the conclusion was drawn that there was no system resonance over the frequency range of the generator. The static volume stiffness of the flow-pulse generator was determined by applying a force to the plunger of the syringe and measuring the pressure obtained inside the fluid-filled flow-pulse generator. The stiffness of the flow-pulse generator was found to be much greater than the stiffness of the heart.

The volume stiffness of the intraventricular balloon was also measured to determine if it was negligible with respect to that of the left ventricle. With the balloon in place at the end of the cannula and filled to the maximal volume used in experiments, no pressure change could be detected by the pressure transducer inside the balloon throughout the frequency range of the flow-pulse generator.

Finally, the frequency response of the pressure transducer used for measuring the pressure perturbations was determined. Using a pressure generator capable of producing sinusoidal pressure variations of up to 60 Hz, the pressure transducer (model SF-1) was found to generate a constant amplitude throughout the frequency range tested.

RESULTS

The effect of the piston frequency of the flow-pulse generator on the intact left ventricle was investigated in five dogs. The piston frequency was varied while the heart rate, ventricular volume, and aortic pressure were held constant. Typical results from a single dog are shown in Fig. 5. Curves A, B, and C represent the temporal variations of volume stiffness which occurred over single cardiac cycles at piston frequencies of 14, 18, and 23.3 Hz, respectively. These piston frequencies represented multiples of 6, 8, and 10 times the same heart rate, as indicated by the number of data points composing the curves of Fig. 5.

From the points composing any of the curves in Fig. 5, volume stiffness is seen to increase gradually from the minimal diastolic values to a maximal value obtained during the peak of systole. The shape of these volume stiffness curves in Fig. 5 indicates that volume stiffness varies as the ventricular pressure and, therefore, may be proportionally related to it.

The data points composing the different curves in Fig. 5 do not appear at the same places during the cardiac cycle since the heart rate was held constant while the piston frequency was changed; therefore, curves were drawn through the points so that comparison of the data for different piston frequencies could be made. Such a comparison of the curves in Fig. 5 indicates that an increase in piston frequency results in a corresponding increase in the diastolic and systolic values of volume stiffness. Small changes in the ventricular pressure which occurred during the collection of the data in Fig. 5 do not affect the results. Comparison of curve A with curve B in Fig. 5, where curve B was obtained at a higher piston frequency, shows that the increase in piston frequency caused an increase in volume stiffness over the entire cardiac cycle. The difference between the curves due to the change in piston frequency was smallest during diastole and increased gradually before reaching a maximal difference during systole. Further, for the same instants in the cardiac period, the difference in curves B and A seems to be approximately the same as the difference in curves C and B. Since these constant differences between curves were obtained as the piston frequency was in-

creased by the same amount in going from 6 to 8 to 10 times the heart rate, the possibility exists that volume stiffness is proportionally related to piston frequency.

DISCUSSION

The experimental technique described in this report provides a means for investigating in vivo the dynamic properties of cardiac muscle. The temporal variations of volume stiffness presented in Fig. 5 indicate how the dynamic compliance varies during a cardiac cycle. The volume stiffness, which is inversely proportional to the dynamic compliance, varies as ventricular pressure, being at a minimum during diastole and at a maximum during the peak of systole. The viscous component of cardiac muscle was investigated by studying the effects of piston frequency on the rate at which the sinusoidal volume changes were introduced. Comparison of the difference between the curves of Fig. 5 indicates that the viscous effect of cardiac muscle varies gradually during the cardiac cycle, being at a minimum during diastole and at a maximum at the peak of systole.

The results of this study agree in general with those of previous investigations. The demonstration of greater stiffness during contraction as compared to relaxation by the present investigation confirms previous work in papillary muscle (1, 5, 7, 10). The presence of cardiac viscosity observed by the present investigation to be greater during systole agrees with previous investigations who have found evidence for systolic but no diastolic viscosity. These investigations have been conducted in both papillary muscle preparations (1, 13) and in vivo preparations (4, 6, 8). Previously published evidence for the existence of myocardial visocisity during diastole was furnished by Lundin (9). In his experiments, the tension of the frog cardiac muscle strips was found to be dependent upon the frequency at which the strips were sinusoidally stretched.

The major difference between the present and previous investigations of the mechanical properties of cardiac muscle is the type of technique employed. Most of the previous techniques utilized papillary muscle or in vitro preparations. The technique described in this report has an advantage over the cited papillary studies because the entire left ventricle is investigated instead of strips of muscle. In addition, the present technique provides a means for quantitating the viscous property of cardiac muscle.

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